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Key Points:

- Timor coral $\delta^{18}O$ and Sr/Ca records SST and SSS at the ITF exit passage
- Timor coral SST and SSS are sensitive to the IOD, whereas ENSO only influences SST
- Timor coral exhibits pronounced low-frequency SST variability

Supporting Information:

- Figure captions
- Supplementary materials

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Twentieth century sea surface temperature and salinity variations at Timor inferred from paired coral $\delta^{18}O$ and Sr/Ca measurements

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Abstract The Indonesian Throughflow (ITF), which represents the global ocean circulation connecting the Pacific Warm Pool to the Indian Ocean, strongly influences the Indo-Pacific climate. ITF monitoring since the late 1990s using mooring buoys have provided insights on seasonal and interannual time scales. However, the absence of longer records limits our perspective on its evolution over the past century. Here, we present sea surface temperature (SST) and salinity (SSS) proxy records from Timor Island located at the ITF exit passage via paired coral $\delta^{18}O$ and Sr/Ca measurements spanning the period 1914–2004. These high-resolution proxy based climate data of the last century highlights improvements and cautions when interpreting paleoclimate records of the Indonesian region. If the seasonality of SST and SSS is not perfectly in phase, the application of coral Sr/Ca thermometry improves SST reconstructions compared to estimates based on coral $\delta^{18}O$ only. Our records also underline the importance of ocean advection besides rainfall on local SSS in the region. Although the El Niño/Southern Oscillation (ENSO) causes larger anomalies relative to the Indian Ocean Dipole (IOD), Timor coral-based SST and SSS records robustly correlate with IOD on interannual time scales, whereas ENSO only modifies Timor SST. Similarly, Timor SST and SSS are strongly linked to Indian Ocean decadal-scale variations that appear to lead Timor oceanographic conditions by about 1.6–2 years. Our study sheds new light on the complex signatures of Indo-Pacific climate modes on SST and SSS dynamics of the ITF.

1. Introduction

The global ocean circulation connects the Pacific to the Indian Ocean through the Indonesian Throughflow (ITF) that acts as the "mix-master" of ocean thermohaline properties in the low latitude [*Gordon*, 2005]. It has been estimated that approximately 80% of the ITF flows through the Makassar Strait, and the rest seeps through the passages between the islands of Maluku and subsequently into the deep Banda Sea (see Figure 1) [*Gordon*, 2005]. The North Pacific water feeds the Makassar Strait's branch of the ITF, while the other branch is primarily composed of the South Pacific Intermediate Water [*Gordon and Fine*, 1996]. A small fraction of the water masses streaming through the Makassar Strait exits the archipelago by flowing south through the Lombok Strait. The majority travels further east and mixes with the South Pacific water in the Banda Sea. The Banda Sea water ultimately enters the Indian Ocean via the Timor and Ombai Straits. Combined, these circuitous ITF passages cool and freshen the Pacific seawaters via strong mixing, sea-to-air heat flux and freshwater inputs in the archipelago [*Ffield and Robertson*, 2005; *Qu et al.*, 2005].

Temporal variations of the ITF conveyor within the Indonesian seas are essential in modifying the thermohaline properties of the exiting waters. Within the Indonesian archipelago, the lowest local salinity is found in the shallow western Indonesian seas. This region, which covers the southern part of the South China Sea to the Java Sea, receives high rainfall and fluvial runoff. Data from moored buoys featured a weakened ITF surface transport at the Makassar Strait during the NW monsoon when the prevailing winds advect the buoyant and less saline Java Sea water toward the strait, therefore restricting the flow of warm Pacific water into

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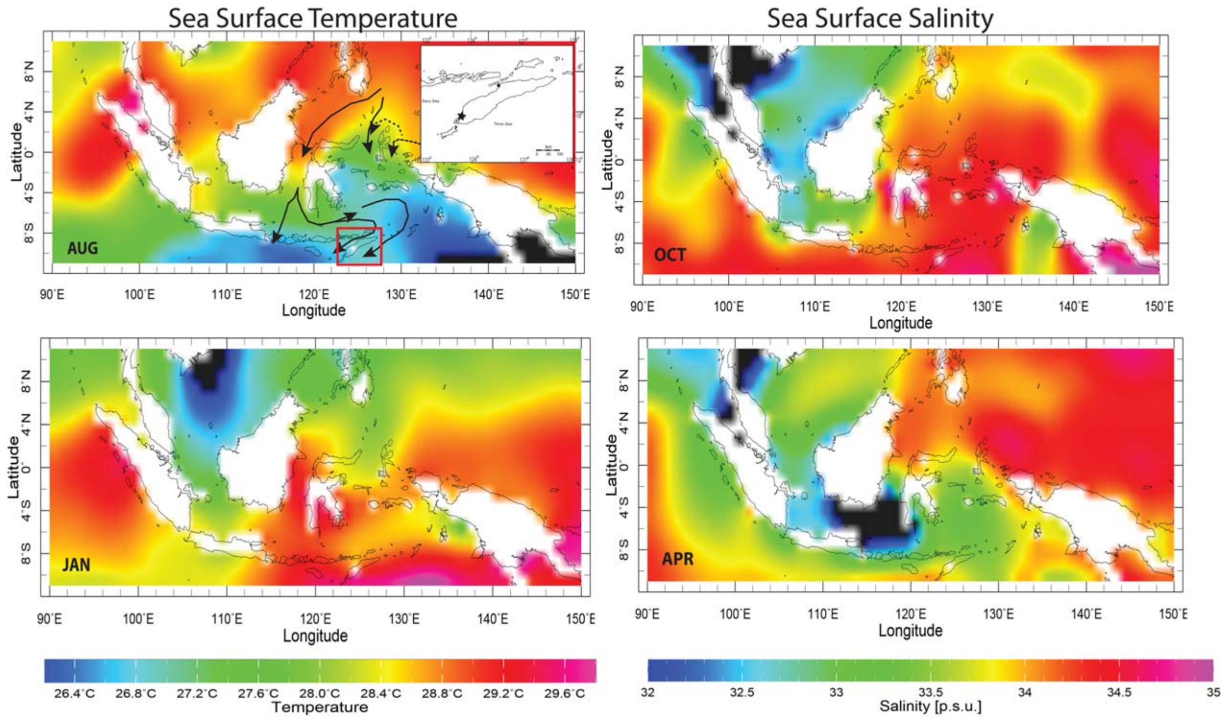

Figure 1. SST and SSS variations over the Indonesian maritime region. (left) SST during the peak of boreal summer (August) and winter (January). The dark arrows mark ITF transports from the Pacific into the Indian Ocean (redraw from *Sprintall et al.* [2009]); and the insert figure shows the location of our studied coral (dark star) and the measurement location from *Sprintall et al.* [2003] (dark circle) along the Ombai Strait. (right) SSS in October when low-salinity water of the Indonesian interior seas is constrained to the west. In April, this water mass is advected furthest eastward onto the Makassar Strait, which causes a seasonal weakening of ITF surface transport. Data from *Levitus and Boyer* [1994].

the Indian Ocean [*Gordon et al*., 2003]. Similar temporal variations also occur in the downstream ITF passageways, for example, in the Ombai Strait where the ITF transport also weakens during the NW monsoon [*Sprintall et al*., 2009].

Ultimately, the longer the route that the Pacific waters travel through the archipelago, the more modified their thermohaline properties in carrying the imprints of oceanographic processes in the Indonesian interior seas.

Situated in the middle of the tropical Indo-Pacific region, the dynamics of the Indonesian seas dance with coupled ocean-atmospheric climate oscillations of this region. On interannual time scales, the reorganization of atmospheric convergence and ocean thermocline depths associated with the ENSO and IOD modify thermohaline transports and properties of the Indonesian seas. A number of strong ENSO events have manifested since the beginning of continuous ITF monitoring campaigns [e.g., the ARLINDO and INSTANT programs; *Sprintall et al*., 2004]. The data reveal that El Niño events, which are characterized by slackened equatorial easterly winds in the Pacific, weaken the ITF transport and cause more saline conditions with the delivery of colder subsurface waters as well as drought anomalies [*Meyers*, 1996; *Field et al*., 2000; *Gordon and Susanto*, 2001]. Furthermore, a strengthened ITF transport has been linked to a positive phase of the IOD [*Gordon et al*., 2010]. In turn, any changes in the strength of the ITF transport may feedback the regional climate by regulating oceanic mass and heat transport in the Indo-Pacific basins [*Godfrey*, 1996; *Lee et al*., 2002]. Unfortunately, it is not yet possible to observe the interplay between Indo-Pacific climate variability and the ITF dynamics over the past century due to the limited span of instrumental data.

High-resolution sea surface temperature (SST) and salinity (SSS) proxy records from ITF passageways that extend over the recent century are therefore crucial in complementing in situ oceanographic campaign measurements. The longer time series would improve our understanding of modern ITF variability and its interplay with the Indo-Pacific climate variability on seasonal to decadal time scales; these only can be obtained with proxy data. In particular, coral skeletons contain a suite of isotopic and trace elemental indicators that provide high (monthly) resolution tropical climate proxy records of the past centuries. Coral oxygen isotopic ($\delta^{18}O$) composition is sensitive to SST and the $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$) variations, while coral

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Sr/Ca ratio primarily reflects changes in SST [e.g., *Correge*, 2006; *Cahyarini et al.*, 2009]. When combined, paired coral δ^{18}O and Sr/Ca measurements allow the reconstruction of $\delta^{18}O_{sw}$ variations by removing the SST contribution from the coral δ^{18}O time series [e.g., *Gagan et al.*, 1998; *Ren et al.*, 2002; *Cahyarini et al.*, 2008; *Nurhati et al.*, 2011]. Seawater δ^{18}O variations in the tropical ocean exhibit a linear relationship with SSS [*Fairbanks et al.*, 1997; *Schmidt*, 1999]. Therefore coral-based $\delta^{18}O_{sw}$ records should be controlled by the precipitation minus evaporation (P-E) balance as well as ocean advection, and have been used as a proxy for salinity. Given the rarity of long and continuous instrumental SSS data, the reconstruction of $\delta^{18}O_{sw}$ is an important contribution of coral records to improve our understanding of past ocean thermohaline and climate variability.

Here, we present the first paired coral δ^{18}O and Sr/Ca record from the ITF exit passageway in Timor (Indonesia) to reconstruct SST and SSS variations at the site (Figure 1). Coral records reflect changes in surface ocean conditions, which are controlled by the imprints of climate variations in the region. To date, coral records from the Indonesian maritime region have relied on coral δ^{18}O as a dual SST-SSS proxy in inferring past Indo-Pacific climate and ocean variability [e.g., *Abram et al.*, 2003, 2008; *Charles et al.*, 2003]. In the Indonesian maritime region, SST, hydrometeorology and wind-driven oceanic advection meddle in a complex interaction of oceanography and large-scale climate modes, and paired coral δ^{18}O-Sr/Ca measurements are the only way to characterize past ocean and climate variability. Here, we present an 89 year long, monthly resolved record of δ^{18}O and Sr/Ca from Timor. In a core-top calibration study published in a previous paper, we have shown that Timor coral Sr/Ca follows SST, while $\delta^{18}O_{sw}$ tracks seasonal changes in SSS at the study site [*Cahyarini et al.*, 2008]. This paper now presents the complete proxy records and investigates the dominant climatic signals that influence Timor SST and $\delta^{18}O_{sw}$/SSS on interannual to decadal time scales.

2. Study Site

We studied a coral from the Ombai Strait, the second largest outlet of the ITF, located in the western side of Timor Island (10°12′S 123°31′E; Figure 1). Therefore, the Ombai Strait represents one of the longest routes of the ITF passageway. Timor experiences strong seasonal SST, rainfall, as well as SSS variations. Situated in the southern hemisphere, Timor SSTs peak in December (29–30°C) and dip in August (26–27°C; Figure 2a, SST). This seasonal SST swing is accentuated by the presence of Ekman downwelling (January–March) and upwelling (July–September) en route and in the Banda Sea that precede Timor along the ITF passage [*Gordon and Susanto*, 2001; *Sprintall and Liu*, 2005]. The regional Indo-Australian monsoon drives the prevailing winds and causes a clear seasonal rainfall pattern in Timor [*Aldrian and Susanto*, 2003]. Rainfall is high during the NW monsoon in November–March, while the opposite occurs when the atmospheric pressure gradient reverses during the SE monsoon in May–September (Figure 2a, rainfall).

Seasonal SSS variations around Timor are sensitive to both horizontal and vertical ocean advections in the region, in addition to the atmospheric P-E balance. Seasonal variability of SSS around Timor exhibits a delayed response to rainfall (Figure 2a, SSS). SSS minima occur in April, which is about 3–5 months after the warmest and wettest month of the year. And a similar offset also occurs between SST and rainfall minima with SSS maxima in October. Enhanced evaporation due to higher wind speeds and an increasingly warmer SST may also contribute to an increase in Timor SSS during this period [*Wyrtki*, 1961; *Sprintall et al.*, 2003]. The eastward propagating South Java Current brings SSS freshening that reaches the Ombai Strait around early April [*Hautala et al.*, 2001; *Sprintall et al.*, 2003, 2010]. The Ekman pumping in the region further accentuates the seasonal SSS in Timor with upwelling that occurs in July to September and downwelling in January–March [*Gordon and Susanto*, 2001; *Hautala et al.*, 2001; *Sprintall and Liu*, 2005].

The phasing of monsoonal climate variability regulates the peak timing of interannual Indo-Pacific climate modes that affect the Indonesian maritime region. For example, the SST anomalies associated with the IOD peak in SON (September-October-November), while ENSO-induced anomalies peak in MAM (March-April-May) [*Izumo et al.*, 2013]. At the Ombai Strait, cooler and saltier conditions were documented during the 1997/1998 strong El Niño event associated with weakened ITF and below-than-average rainfall anomalies [*Sprintall et al.*, 2003].

Since seasonal warmer months are not in phase with less saline conditions around Timor, coral δ^{18}O records alone would not provide the necessary information to understand ocean and climate variability at our site. This is because warm SST and less saline conditions deplete coral δ^{18}O values and vice versa. This fact

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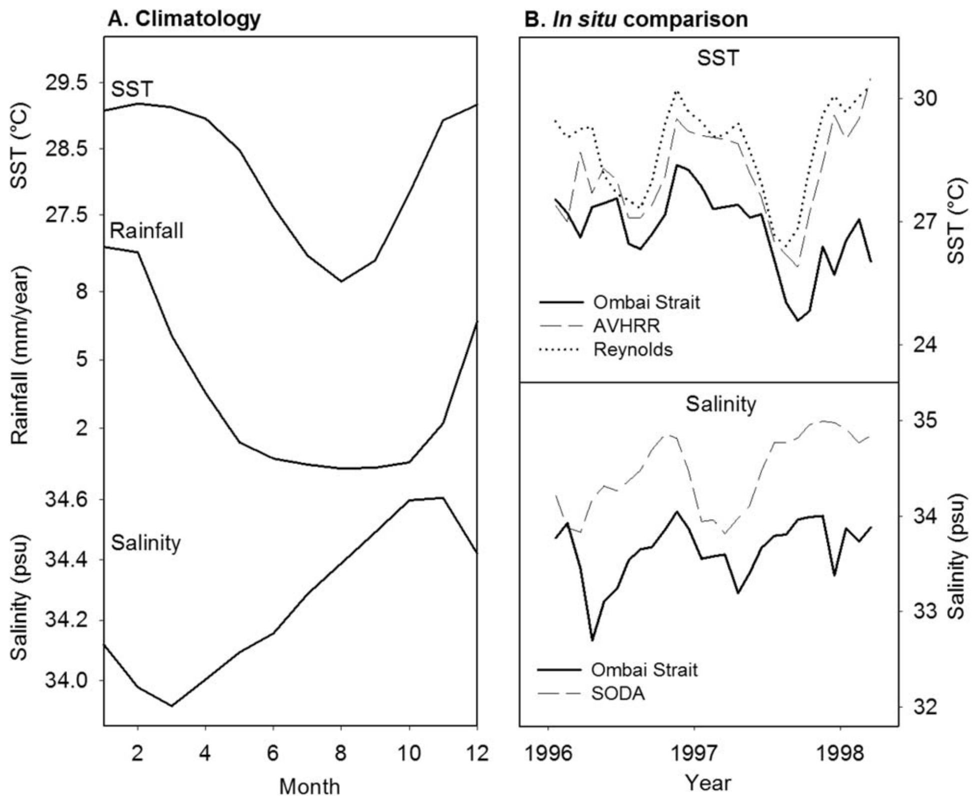

Figure 2. (a) Monthly climatology of SST, rainfall, and SSS at Timor over the period 1985–2004. Data from AVHRR SST [*Casey et al*., 2010], CMAP rainfall [*Xie and Arkin*, 1997], and SODA SSS [*Carton and Giese*, 2008]. (b) SST and SSS from measurements at the Ombai Strait [*Sprintall et al*., 2003] and gridded instrumental data over the available period 1996–1998. OISST from *Reynolds et al*. [2002].

highlights the importance of coral Sr/Ca thermometry in combination with coral δ^{18}O data to better understand long-term SST and SSS variations at our site.

3. Material and Methods

A 180 cm long core from a massive *Porites* sp. colony was drilled in Kupang Bay, west of Timor Island in June 2004. The top of the colony was at about 3 m water depth. The core was cut into 4 mm thick slabs, rinsed in an ultrasonic bath, and oven-dried at 50°C for 24 h. The x-radiographs of the slabs show pronounced annual density bands that allow the development of a precise chronology. The average annual extension rate is 1 $\pm$ 0.5 cm/yr. Sampling transects were selected following the main growth axis to subsample coral powders at 1 mm increments. This allowed the generation of proxy time series with about monthly resolution. The powdered samples were split for δ^{18}O and Sr/Ca analyses. The coral stable isotope compositions were analyzed using a Thermo Finnigan Gasbench II Delta Plus with an analytical precision of $\pm$0.06‰ (1σ) reported relative to the NBS19 standard. The Sr/Ca ratios were measured on a Spectro Ciros Inductively Coupled Plasma Optical Emission Spectrophotometer (ICP-OES) at the University of Kiel following methods published by *Schrag* [1999] and *de Villiers et al*. [2002] with an analytical precision of $\pm$0.15% (1σ).

The coral chronology was assigned via Sr/Ca as a SST proxy, yielding coral-based climate records that extend from May 1914 to June 2004. We assume December and August as the warmest and coolest months, respectively, according to instrumental observations. A linear interpolation was applied to assign ages in between anchored points using the Analyseries software [*Paillard et al*., 1996], prior to the even spacing of the data points into a monthly (12 points per year) resolution. The uncertainty of the age model is approximately 2 months in any given year. This error is noncumulative. The age error of the complete chronology is difficult to estimate, but previous studies suggest that coral chronologies may be accurate within $\pm$1 year [*Quinn et al*., 1998].

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Coral Sr/Ca values were calibrated with SST using 4 × 4 km spatially resolved Advanced Very High Resolution Radiometer (AVHRR) SST over the period of January 1985 to June 2004 [*Casey et al*., 2010]. The accuracy of the high-resolution AVHRR SST may be affected by cloud cover [e.g., *Zhang et al*., 2009], which is a potential problem in the Indonesian region. However, it captures local SST more accurately than other gridded SST data sets when compared with an in situ SST that is available from the Ombai Strait over the period of January 1996 to March 1998 (Figure 2b) [*Sprintall et al*., 2003]. The monthly coral Sr/Ca-SST (AVHRR) calibration yields: $Sr/Ca = -0.04 \pm 0.002 SST + 9.712 \pm 0.07$ ($R = -0.67$, $N = 234$, $p < 0.0001$). The slope value of regression is within the −0.04 to −0.08 mmol/mol/°C range of published values for *Porites* corals [*Correge*, 2006]. There is a high ($R = -0.89$) correlation between coral Sr/Ca and the Ombai in situ data [i.e., *Sprintall et al*., 2003] with a slope of −0.06 mmol/mol/1°C. Although short in temporal coverage, the higher correlation with in situ SST measurements hints that our coral may record local temperature more reliably than gridded satellite-based SST products in this region. We further compare our coral-derived SST record with 1° × 1° OISST v.2 for November 1981 to June 2004 [*Reynolds et al*., 2002], as well as the Extended Reconstruction Sea Surface Temperature (ERSST) v.3b that covers the entire span of our record but with a lower (2° × 2°) spatial resolution and higher uncertainty during the time prior to the satellite era [*Xue et al*., 2003; *Smith et al*., 2008].

A coral-based $\delta^{18}O_{sw}$ record was derived by removing the SST contribution on coral $\delta^{18}O$ by taking the instantaneous changes in $\delta^{18}O$ and Sr/Ca or using centering method, i.e., normalized the data to its mean value [e.g., *Ren et al*., 2002; *Cahyarini et al*., 2008]. We used Timor's Sr/Ca-SST (AVHHR) calibration slope of −0.04 mmol/mol/°C (which represents the slope via a geometric mean regression) and the empirical $\delta^{18}O_{coral}$-SST values of −0.21‰/°C [*Ren et al*., 2002]. *Cahyarini et al*. [2008] have shown that monthly $\delta^{18}O_{sw}$ reconstructed using these parameters tracks monthly SSS at Timor.

A linear relationship between $\delta^{18}O_{sw}$ and SSS has been shown widely in the tropical oceans [*LeGrande and Schmidt*, 2006]. We assessed our coral-based $\delta^{18}O_{sw}$ as a SSS proxy against available observational and/or reanalysis SSS data sets. A short in situ SSS data is also available from the Ombai Strait record (January 1996 to March 1998) from *Sprintall et al*. [2003]. Given the challenges of having a continuous in situ SSS record, we also compared our SSS proxy record with the gridded Simple Ocean Data Assimilation (SODA) [*Carton et al*., 2000; *Carton and Giese*, 2008]. There are much less observational SSS data available than for SST. SODA combines field information of temperature, salinity, sea level, and wind to estimate monthly SSS variations on a global scale. Here, we use SODA v.2.1.6 for the period January 1958 to June 2004. The SODA data uses the European Center for Medium Range Forecasts ERA-40 atmospheric reanalysis from 1958 to 2001 and daily wind data the QuikSCAT scatterometer that may have less wind error for the tropics but only started in 2000 [*Carton and Giese*, 2008].

We assessed significant frequencies contained in the coral records and a number of climate indices using a multitaper single spectrum analysis following *Vautard et al*. [1992]. On interannual time scales, we assessed our coral records against the Dipole Mode Index (DMI) as an index for the Indian Ocean Dipole and NINO3.4 SST anomaly as an ENSO index. The DMI is calculated as the SST anomaly gradient between the western (50°E–70°E and 10°S–10°N) and southeastern equatorial Indian Ocean (90°E–110°E and 10°S–0°N). We use the DMI calculated using HadISST data set without detrending and time filtering retrieved from http://www.jamstec.go.jp/frcgc/research/d1/iod/DATA/dmi_HadISST_1871–1997_wodetrend.txt. The NINO3.4 index is the average SST anomaly in the central equatorial Pacific (5°N–5°S, 170°W–120°W), the center of action of ENSO. We use the NINO3.4 index calculated using Kaplan Extended v2 that was retrieved from http://iridl.ldeo.columbia.edu/SOURCES/.Indices/.nino/.EXTENDED/.NINO34 [*Kaplan et al*., 1998; *Reynolds et al*., 2002]. On decadal time scales, we assessed decadally filtered coral records, DMI, NINO3.4 and the Interdecadal Pacific Oscillation (IPO) index. The IPO index, which is a multidecadal SST mode with similar spatial expression as ENSO, was retrieved from www.iges.org/c20c/IPO_v2.doc [*Power et al*., 1999; *Folland et al*., 2002].

4. Results and Discussions

4.1. Coral $\delta^{18}O$ as a Dual Proxy for SST and SSS

The Timor coral $\delta^{18}O$ record is characterized by clear annual, interannual and decadal variations, and a moderate long-term trend toward depleted coral $\delta^{18}O$ values (Figure 3a). Annually, Timor coral $\delta^{18}O$

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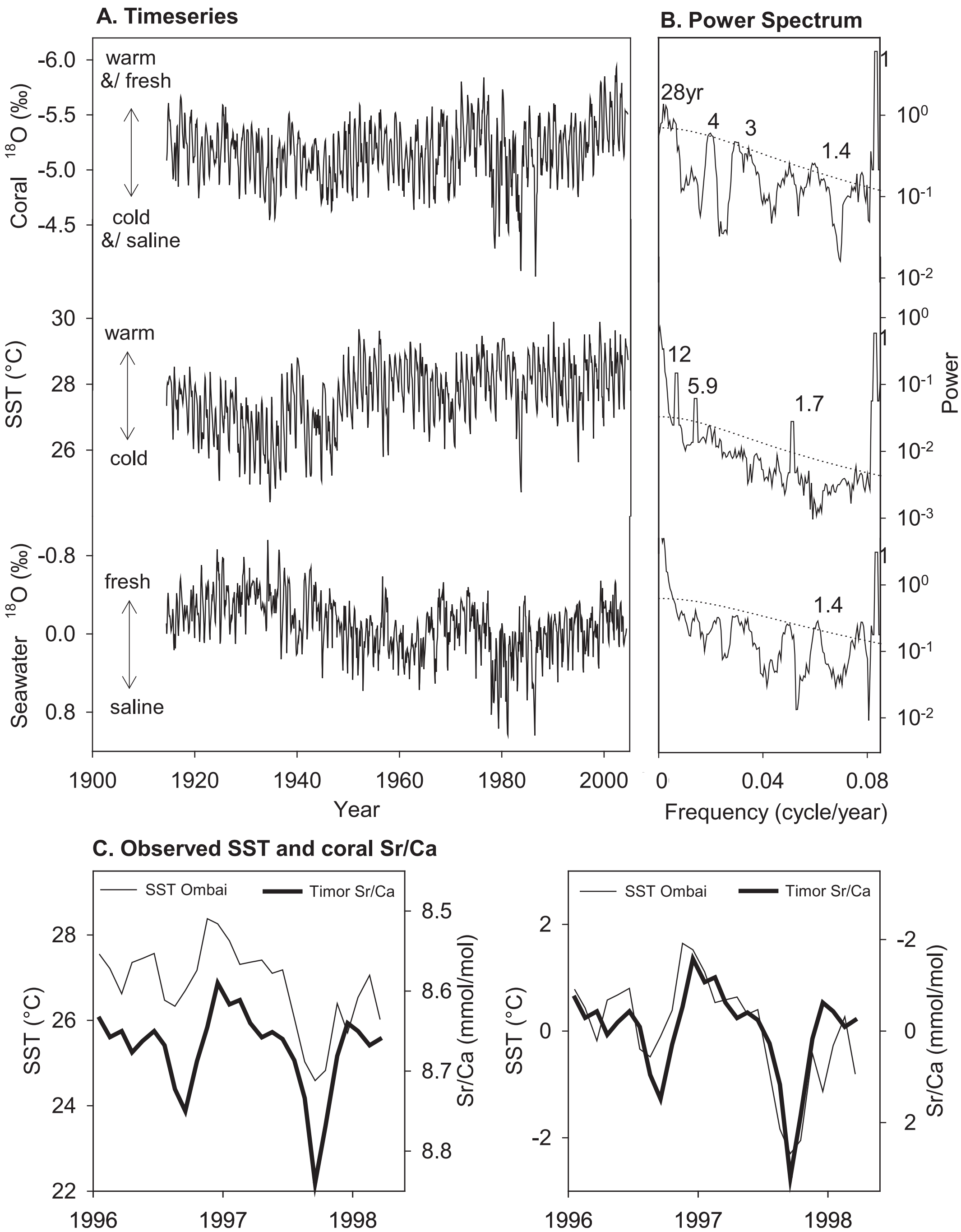

Figure 3. Timor coral proxy records. (a) Coral δ^{18}O, Sr/Ca-based SST, and $\delta^{18}O_{SW}$. (b) Spectral analysis of the Timor coral records with 95% confidence interval (dotted lines). Significant frequencies (in years) are shown. (c, left) Monthly variation of measured SST at Ombai (data from *Sprintall et al.* [2003]) and coral Sr/Ca for period of 1996–1998, (c, right) standardized data. For longer data see Figure S1 in the supporting information.

values are most enriched in September—a period between annual SST minima (August) and SSS maxima (October) conditions, suggesting the contribution of the two parameters on Timor coral δ^{18}O. Similarly, Timor coral δ^{18}O values are most depleted in March, which is the period between the annual SST maxima (December) and SSS minima (April) of the year. The coral δ^{18}O record shows several distinct positive anomalies between 1977 and 1986. Repeated measurements over this interval confirm reproducible results (see Figure S1 in the supporting information). Therefore, it is unlikely that the coral δ^{18}O anomalies are related to analytical problems. Theoretically, coral δ^{18}O can be biased by vital effects and diagenesis [*Juillet-Leclerc*

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et al., 2009]. Both of these problems should also influence coral Sr/Ca. In fact, coral Sr/Ca appears to be even more sensitive to anomalous coral growth and/or diagenesis [*de Villiers et al*., 1994; *McGregor and Gagan*, 2003; *Sayani et al*., 2011]. In order to assess the potential climatic importance of these anomalies, they should be reproduced using additional coral cores from Timor.

The influence of SSS in the Timor coral δ^{18}O record, which differs seasonally from SST, cautions the use of coral δ^{18}O alone to infer past SST changes in the region [see also *Cahyarini et al*., 2008]. In the absence of coral-based SST proxy data, many studies had estimated coral δ^{18}O-SST relationship via univariate linear regression [e.g., *Abram et al*., 2008; *Gagan et al*., 1994, 1998]. This may not be an appropriate model considering that SST and $\delta^{18}O_{sw}$ tend to covary during the calibration period [*Cahyarini et al*., 2008]. Such a methodological problem arising from the use of univariate coral δ^{18}O-SST linear regression may cause a bias in the slope of the coral δ^{18}O-SST relationship, that may ultimately lead to an under or overestimation of seasonal variability and long-term SST changes. Using coral δ^{18}O as a more general climate proxy, in the sense that enriched δ^{18}O values indicate cooler and drier conditions while depleted values indicate warmer and wetter conditions [e.g., *Charles et al*., 2003, *Abram et al*., 2008], may also be problematic in many Indonesian regions due to (i) the complex, out-of-phase relationship between the seasonal cycle of SST and SSS as discussed herein, and (ii) the distinct seasonality of the dominant climate modes. For example, IOD induced SST anomalies peak in SON, ENSO-induced anomalies peak in MAM [*Izumo et al*., 2013].

The application of multivariate linear regression (MLR) that accounts for possible covariance between SST and $\delta^{18}O_{sw}$ at our site yields more realistic coral δ^{18}O-SST regression slopes compared to the univariate approach. At Timor, the presence of a strong SSS signal would lessen the SST contribution to the coral δ^{18}O. Therefore, we would expect the slope of the monthly coral δ^{18}O-SST calibration to be lower relative to the reported values that range from -0.18 to $-0.22‰/°C$ [*Weber and Woodhead*, 1972; *Gagan et al*., 1994; *Wellington et al*., 1996]. The coral δ^{18}O-SST calibration slopes derived using univariate linear regression are indeed smaller, at -0.12 ± 0.02 and $-0.08 \pm 0.03‰/°C$ with AVHRR SST and Ombai in situ SST, respectively. We then applied the MLR calibration using in situ SST and SSS measurements from the Ombai Strait. The MLR model considers both coral δ^{18}O-SST and coral δ^{18}O-$\delta^{18}O_{sw}$ relationships, therefore taking into account the covariance between SST and $\delta^{18}O_{sw}$. The MLR calibration with in situ Ombai data yields a coral δ^{18}O-SST slope of $-0.17 \pm 0.04‰/°C$ ($R = -0.69$, $p < 0.001$). Considering the error, this is consistent with the reported empirical values. The coral δ^{18}O-SSS slope is $0.01 \pm 0.11‰$/psu. The slopes are less realistic when gridded SST and SSS products were used, suggesting the need of in situ calibrations of coral proxy data in the Indonesian maritime region. Also, modeled $\delta^{18}O_{sw}$-SSS relationships from the Timor region vary between 0.1 and 0.3‰/psu [*Delaygue et al*., 2000], while the regional estimate using sparse observational data from *Schmidt* [1999] yields 0.44 and 0.28‰/psu [*Le Grande and Schmidt*, 2006]. More local observational data are needed to better estimate the $\delta^{18}O_{sw}$-SSS relationship of paleoclimate records.

4.2. Coral Sr/Ca-Based SST Record

Our coral Sr/Ca-derived SST record (Figure 3a, middle) captures observed seasonal variations in local SST. The correlation between coral Sr/Ca is highest with in situ Ombai SST ($R = -0.89$; January 1996 to March 1998) compared to gridded SST data sets over the same period. The correlations are -0.67 with AVHRR and -0.62 with Reynolds SST, respectively (see Figures S2 in the supporting information). Over the entire study period (May 1914 to June 2004), the correlation with ERSST is -0.61. There is more low-frequency variability exhibited by the coral-based SST record than the ERSST (see Figure S3 in the supporting information). Assessing the potential influence of rainfall and/or SSS on our coral Sr/Ca, we find no indication of such a case. The higher correlation with in situ SST data hints at the fidelity of corals to record local temperature more reliably than gridded SST products in this region. Moreover, infrared satellite data may be biased due to the high cloud cover over the Indonesian region [e.g., *Zhang et al*., 2009].

Spectral analysis of our coral-based SST record reveals a number of high and low-frequency climate variability with a long-term warming (~1.7°C) trend over the 20th century (Figure 3). These high (i.e., annual, quasi-biennial, interannual) and low (quasi-decadal and decadal) frequency climate variability have been documented in a coral δ^{18}O record from the entrance of the ITF passageway [*Charles et al*., 2003].

Coral δ^{18}O is still often used to reconstruct SST. Here, we show that coral Sr/Ca only is a promising tool for SST reconstruction. Spatial correlation coefficients between monthly ERSST with coral Sr/Ca-based SST range between $R = 0.6$–0.8. This is higher than the results obtained for coral δ^{18}O ($R = 0.2$–0.4; Figure 4).

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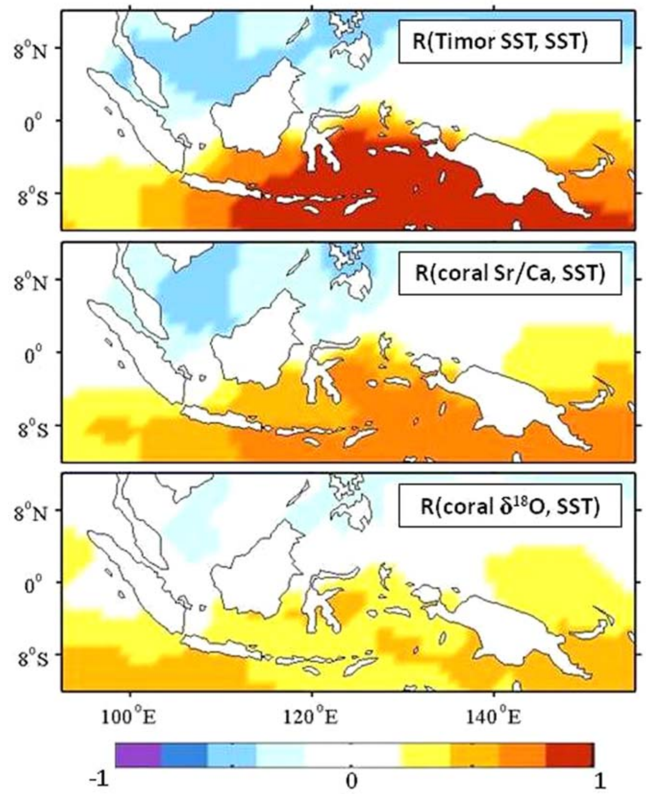

Figure 4. Spatial correlation between monthly SST with: (top) Timor SST, (middle) coral Sr/Ca-based SST, and (bottom) coral δ^{18}O-based SST over the period November 1981 to June 2004. SST data from *Reynolds et al.* [2002]. The figures show the improvement made in capturing regional SST imprints using coral Sr/Ca over coral δ^{18}O as a SST proxy in the region.

This confirms that coral Sr/Ca-based SSTs capture the spatial correlation of Timor SST and regional SST as observed in instrumental data.

4.3. $\delta^{18}O_{sw}$-Based SSS Record

The seasonal variability in the Timor $\delta^{18}O_{sw}$ record (Figure 3a, bottom) confirms the observed in situ SSS data from Ombai Strait. *Cahyarini et al*. [2008] assessed the core top section of the Timor coral with instrumental and model (SODA) SSS data and showed coherent seasonal cycles between the coral-based and instrumental SSS records (see Figure S4 in the supporting information). Timor $\delta^{18}O_{sw}$ shows higher SSS during the NW monsoon (September to February). The coral-based SSS record also confirms a delayed response of seawater freshening, which lags the wettest months by several months. Thus, SSS may also be influenced by ocean advection in the nearby seas. In contrast, the $\delta^{18}O_{sw}$ does not exhibit significant interannual and decadal variations that characterize the coral Sr/Ca-based SST record (Figure 3).

The accurate estimation of SSS from coral $\delta^{18}O_{sw}$ records requires reliable local or regional $\delta^{18}O_{sw}$-SSS relationships. Studies on $\delta^{18}O_{sw}$ modeling in the region have estimated a sensitivity in the range of 0.1–0.44‰/psu [e.g., *Schmidt*, 1999; *Delaygue et al*., 2000; *LeGrande and Schmidt*, 2006]. With seasonal variability of $\delta^{18}O_{sw}$ at about 0.32‰ and SSS of about 1 psu (from *Levitus and Boyer* [1994]) and 0.4–0.63 psu (from SODA using the whole available period from 1958 and from 2000 when the satellite measurement is available), we can infer that $\delta^{18}O_{sw}$ may be enriched by about 0.31–0.8‰/psu. This huge spread illustrates that any progress in coral-based SSS reconstructions strongly depends on more and better observations to constrain the $\delta^{18}O_{sw}$-SSS relationship. SSS time series from stationary points as well as ARGO floats are exceptionally scarce in the Indonesian maritime region. Reanalysis SSS products that often contain bias in their mean values and seasonality from observational data would largely benefit from a growing number of coral-based paleo-SSS reconstructions.

4.4. Sensitivity of Timor SST and SSS to Indo-Pacific Climate Variability

4.4.1. Interannual Variability

The signatures of IOD and ENSO on Timor SST vary on interannual time scales, reflecting their complex impact on the Indonesia maritime region. The correlations of the 2–7 years band-passed coral Sr/Ca record with the NINO3.4 and DMI over the period 1914–2004 are 0.20 and 0.18, respectively (see Figure 5a, left). The fairly low correlations that we see in our record are consistent with instrumental data (Figure 5b, left). During the warm phase of ENSO, Timor sits on the transition of regions with positive SST anomalies (i.e., the interior western Indonesia seas) versus negative SST anomalies (i.e., eastern Indonesia; Figure 5b, top left). Indeed, instrumental in situ measurements show that the seasonal cycle of Timor SST is large, while interannual variability is small [*Sprintall et al*., 2003; *Qu et al*., 2005]. In the case of the IOD, although it has a

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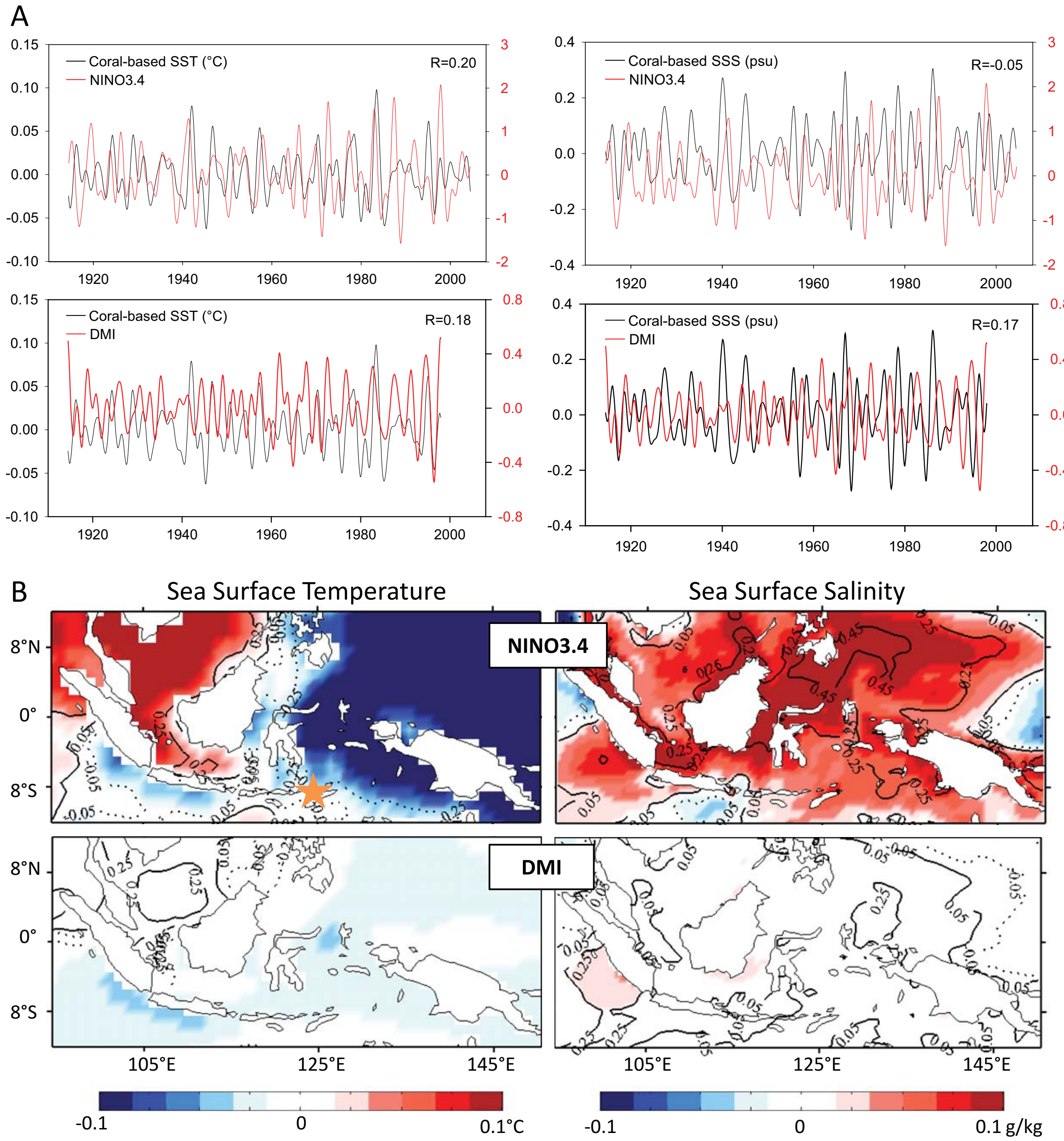

Figure 5. (a) Interannual (2–7 years) band-passed Coral-based SST and SSS records. (left) Interannual (2–7 years) band-passed coral-based SST compared to (top) NINO3.4 index and the (bottom) DMI. (right) Same, but for coral-based SSS instead of SST. (b) The regression (color) and correlation (contour) of 2–7 years band-passed ENSO and IOD indices on SST and SSS anomalies in the Indonesian maritime region over the period November 1981 to June 2004. The location of our coral is marked (star on the top left figure). These figures highlight the varying imprints of ENSO and IOD on Indonesian SST and SSS.

relatively uniform imprint in the region (i.e., lower SSTs throughout most of Indonesian seas during positive IOD events), the magnitude of SST anomaly is masked by the strong seasonal SST variability at Timor. The imprint of SST anomalies during the IOD events are much weaker than ENSO (see the regression colors on Figure 5b, left) but with fairly similar correlations with Timor SST.

Our paired coral δ^{18}O and Sr/Ca measurements highlight the distinct signatures of IOD and ENSO on Timor SSS. The correlations of 2–7 years band-passed coral-derived $\delta^{18}O_{sw}$ record with the DMI and NINO34 over the period 1914–2004 are -0.17 ($p < 0.0001$) and -0.05 ($p < 0.1$). Comparing these correlations with those with coral Sr/Ca, we find that IOD influences both Timor SST and SSS whereas ENSO only makes its mark on SST at our site (see Figure 5a, right). It is surprising to find an insignificant ENSO signature on Timor SSS

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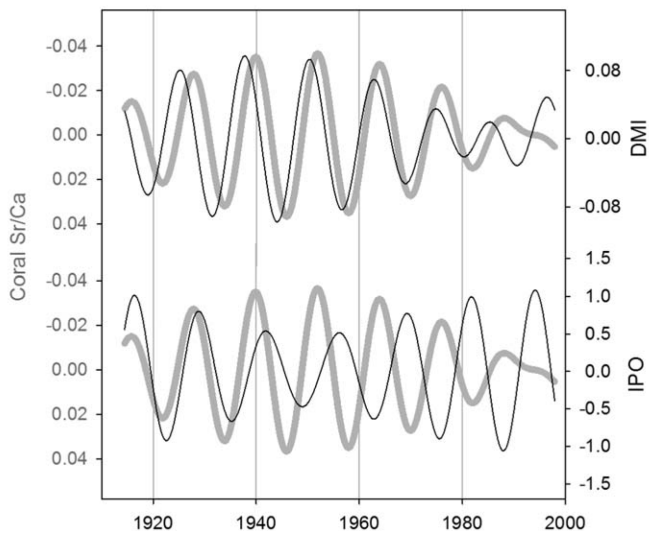

Figure 6. Quasi-decadal (11–14 years) band-passed coral Sr/Ca (in gray) with the (top) Dipole Mode Index (in black) and the (bottom) Interdecadal Pacific Oscillation (in black).

considering that rainfall deficit and shoaling of western Pacific thermocline during El Niño events may cause more saline conditions at our site. Reanalysis SSS products also support the stronger SSS anomaly imprint and correlation of NINO3.4 with Timor SSS compared to the DMI (Figure 5b, right). However, it is difficult to confirm this given the uncertainty in reanalysis SSS data. Taken together, we highlight the importance of identifying SST and SSS anomalies during ENSO and IOD events to better understand the signatures of Indo-Pacific climate variability on paleoclimate proxy records.

4.4.2. Decadal Variability

On decadal time scales, our coral records exhibit a higher sensitivity to Indian Ocean decadal climate variability, which is distinct from those observed in the Pacific basin (Figure 6). The 11–14 years band-passed DMI is highly correlated to Timor SST (R $= -0.92$, $p < 0.0001$) and SSS (R $= 0.91$, $p < 0.0001$) over the period 1914–1997 with the DMI leading Timor SST and SSS by 1.6–2 years. The presence of decadal-scale IOD variability in our coral record is in line with general coupled ocean-atmospheric model results, which suggest an important role of ocean dynamics and zonal wind anomalies for the decadal-scale climate variations [*Ashok et al*., 2004]. Positive DMI or IOD correspond to colder and more saline conditions at Timor, and have been linked to a stronger ITF transport [*Gordon et al*., 2010]. Corals from the tropical Pacific have also revealed SST variations of a similar frequency [e.g., *Nurhati et al*., 2011]. However, the quasi-decadal SST variability in the Indian Ocean clearly differs from that observed in the Pacific Ocean regarding its temporal evolution as well as its amplitude modulation (see Figure S5 in the supporting information). Within our studied time interval, a period of strong quasi-decadal variations in the Indian Ocean is associated with weak variations in the Pacific.

Finally, our coral record exhibits more pronounced low-frequency SST variability compared to ERSST. This may be attributed to a higher uncertainty in the reanalysis data set prior to the satellite era [e.g., *Solomon and Newmann*, 2012], local climatic influences amplifying SST variations [e.g., *Zhang et al*., 2013], as well as possible non-SST related influences on Timor Sr/Ca on longer time scales [e.g., *Grove et al*., 2013].

5. Conclusions

We present the first high-resolution, paired coral δ^{18}O and Sr/Ca records from Ombai Strait, Timor, a key exit passage of the Indonesian Throughflow. The record extends from 1914 to 2004. Since coral δ^{18}O is influenced by multiple environmental parameters (i.e., SST, $\delta^{18}O_{sw}$, and SSS, the latter controlled by the P-E balance and oceanic advection) in the Indonesian region, this compromises the fidelity of SST estimates using coral δ^{18}O measurements alone. Sr/Ca measurements as an established SST proxy allow us to improve SST reconstructions, and paired coral δ^{18}O and Sr/Ca measurements can be used to derive the residual $\delta^{18}O_{sw}$ time series as a proxy for SSS.

Paired Timor coral δ^{18}O and Sr/Ca records reveal the impact of Indo-Pacific climate variations on SST and SSS at the exit passage of the ITF:

1. Our coral Sr/Ca-based SST and $\delta^{18}O_{sw}$-based SSS records capture the strong seasonality at Timor that results from the regional monsoon forcing. The seasonality is characterized by SST and rainfall that peak in December and dip in August, while SSS is lowest in April and highest in October. This highlights the important role of ocean currents in the region in addition to the hydrological P-E balance in regulating local SSS variability.

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2. On interannual time scales, coral-based Timor SST and SSS are sensitive to the Indian Ocean Dipole, whereas ENSO only influences SST but not SSS at our site. Here, we emphasize that the varying imprints of Indo-Pacific climate modes on SST and SSS over the Indonesia maritime region as evident in our coral record, should be taken into account when interpreting paleoclimate records from Indonesia.
3. On decadal time scales, there is a strong correlation between Timor and decadal IOD variations with the decadal IOD leading Timor SST and SSS by about 1.6–2 years. This decadal climate variability in the Indian Ocean differs from those observed in the Pacific Ocean. During the time period studied, a period of high-amplitude decadal variations in the Indian Ocean is associated with weak variations in the Pacific.
4. The utility of coral Sr/Ca thermometry improves SST reconstruction in the ITF passageway and over the Indonesian maritime region rather than using coral $\delta^{18}O$ only.
5. Our coral record exhibits more pronounced low-frequency SST variability compared to the reanalysis SST product. More accurate estimates of low-frequency SST variability may improve the detection of secular warming trends in this climatically important region.

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Erratum

The affiliation footnotes for Intan Suci Nuhati should have been the following: Center for Oceanography and Marine Technology, Surya University, and (now at) Center for Environmental Sensing and Modeling, Singapore-MIT Alliance for Research and Technology. Author Edvin Aldrian should have only been affiliated with the Meteorological Climatological and Geophysical Agency (BMKG). These footnotes have since been corrected and this version may be considered the authoritative version of record.

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